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Effect of dust, humidity and air velocity on efficiency of photovoltaic cells

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ABSTRACT

The environmental and economical merits of converting solar energy into electricity via photovoltaic cells have caused an ever increasing interest among developed and developing countries to allocate more budget on photovoltaic systems in order to boost up their efficiency in recent years. Besides the material and design parameters, there are several omnipresent factors such as dust, humidity and air velocity that can influence the PV cell's performance. There have been a handful of studies conducted on the effect of various influential parameters on the efficiency and performance of photovoltaic cells; however none has taken all these three parameters into account simultaneously. In this study the impact of dust accumulation, humidity level and the air velocity will be elaborated separately and finally the impact of each on the other will be clarified. It is shown that each of these three factors affect the other two and it is concluded that in order to have a profound insight of solar cell design, the effect of these factors should be taken into consideration in parallel.

Contents

1. Introduction

Solar energy is a free, inconsumable and clean source of energy which is the focus of many recent researches in energy field, many of which are about overcoming the inefficiencies of solar power systems. Through this introductory section, the interested reader can come up with the idea of how sunlight can be converted to electricity using semiconductors and what are the crucial parameters that can influence the conversion efficiency of photovoltaic systems.

1.1. Solar energy

The energy received from the sun on the earth's surface in one hour equals to the amount of approximately one year energy needs of the earth. Sun acts like a black body radiator with the surface temperature of 5800 K which leads to a 1367 W/m^2 energy density over the atmosphere [1–3]. While designing PV systems, the spectral factor should be studied and taken into consideration. The importance of having a profound knowledge of the sun spectrum lies on the fact that this knowledge can help to understand the effects of atmosphere on the radiation and guides us to select the best materials for solar cells [4].

As it is observed in Fig. 1, almost the entire spectrum at low temperatures is located outside the visible range, specifically in the infrared section. The visible range contains the highest energy

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Nomenclature

AM	air mass
I_l	cell current due to photons (A)
I_s	reverse saturation current (A)
T	cell temperature (K)
q	electron charge (C)
k	Boltzmann's constant (J/K)
ν	voltage across the diode (V)/viscosity (m^2/s)
G_o	reference irradiance level (KW/m^2)
$I_l(G_o)$	cell current at G_o (A)
G	irradiance level (KW/m^2)
NOCT	nominal operating cell temperature
T_a	ambient temperature (°C)
T_c	cell temperature (°C)
T_s	cell surface temperature (°C)
η	solar cell's conversion efficiency
A_c	module's effective area (m^2)
V	wind velocity (m/s)
T_{ref}	reference temperature (°C)
β_{Tref}	temperature coefficient
EHP	electron-hole-pair
G_s	solar irradiance (KW/m^2)
$I_l(G)$	cell current at G (A)
P_{max}	maximum power (W)
P_{mea}	mean power output (W)
I_m	current at maximum power (A)
V_m	voltage at maximum power (V)
I_{sc}	short circuit current (A)
V_{oc}	open circuit voltage (V)
FF	fill factor (%)
$q''_{cond.}$	conduction heat flux over PV cell (W/m^2)
$q''_{conv.}$	convection heat flux over PV cell (W/m^2)
K	material conductivity (W/m K)
H	convection coefficient (W/m^2 K)
Pr	Prandtl number
Re_x	Reynolds number
Nu_x	Nusselt number

density. Therefore, the materials chosen for the solar cells should have the capability to absorb the energy in the visible range.

Sunlight is comprised of direct radiation – also named beam radiation – which is the sunlight received by the surface of earth,

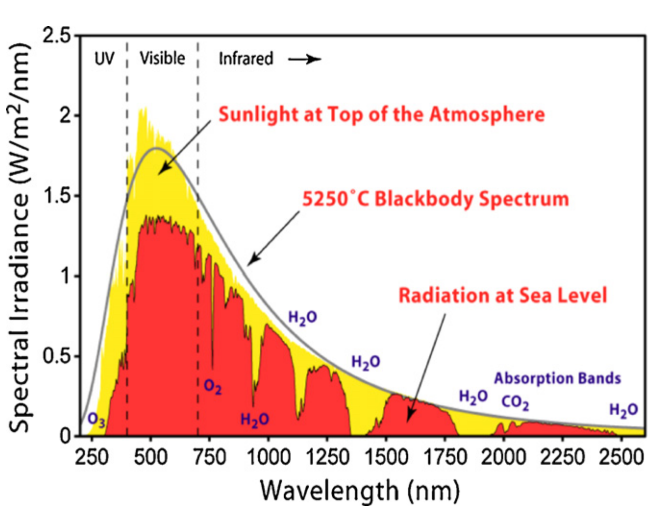

Fig. 1. The solar radiation spectrum regarding to its wavelength [5].

diffuse radiation which is also called scattered sunlight and albedo radiation that is the reflected sunlight from the ground. The sum of these three components of light is named global radiation [6,7]. When the global radiation enters the atmosphere of the earth, molecules in the atmosphere might cause three cases, they may absorb, scatter or pass the light unaffected [8]. The ultra violet region of sunlight is mostly absorbed by the ozone layer of the atmosphere while the CO_2 and water vapour particles are influential on the visible and infrared regions [9]. The objects on the ground level might also reflect or absorb the light.

Air mass is a critical factor affecting the amount of energy absorbed on the ground surface. As a result of particulate matter existence in atmosphere and the length of the path solar light travels through atmosphere, the AM0 irradiance level – just above the atmosphere – drops from 1367 to 1000 W/m^2 corresponding to the AM1 – at sea level. AM1.5 is addressed as the standard test condition in solar cell design [10].

1.2. Photovoltaic phenomenon and physics of PV cell

When light hits the surface of materials it might be reflected, transmitted or absorbed mostly converting the photon energy to heat. However some materials have the characteristic of converting the energy of incident photons in to electricity. Photons give their energy to electrons based on the conservation of momentum and energy principals. The liberated electrons can move across the crystal. This is called photovoltaic effect [3,11].

These materials which have an energy band gap between the conduction band and the valence band are named semiconductors. Valence band is the energy level in which the electrons are bound to host atoms, while the conduction band is the energy level of electrons taken from an external source causing them no longer bound to the host atom. At the absolute zero temperature no electron is in the conduction band. As the temperature elevates some electrons receive energy and go up from the valence band to the conduction band creating an energy-hole-pair (EHP). If the energy of the incident photon is larger than the energy band gap of the semiconductor the photon energy will be absorbed and EHP will be produced. The remainder of the difference between photon energy and band gap dissipates into heat. Semiconductors are classified into two groups, the direct band gap and indirect band gap semiconductors. A direct band gap material can be several times thinner than the indirect band gap ones while still capable of absorbing a considerable amount of incident radiation [3,11,12].

There exists an electrical field in semiconductor materials to which the liberated electrons can drift. The force caused by this electrical field leads the electrons to travel to n-side of the junction whereas the holes to its p-side. Adding some materials by means of doping invigorates the electrical field. For more clarification, as an instance, phosphor gives electron to silicon and boron adds holes creating n type and p type silicon respectively. The current from p-side to n-side through external wire depends on the number of EHPs generated in the junction; this current is named photo current. To maximize photo current the number of photons absorbed in either junction itself or the diffusion length should be increased [3,12].

1.3. PV cells

Solar cell also called PV cell is a device that can produce a voltage difference when a source of light shines on it. When the solar cell gets connected to a circuit via wires, the electrical current flows through the wire, as a result work will be produced.

French scientist Edmund Becquerel first discovered that light can be converted to electricity using some kinds of materials in 1839, later in 1876 Adams and Day noticed the selenium's photovoltaic effect. After a few years, the American Charles Frits invented

the first solar cell. In 1954 Chapin, fuller and Pearson increased the solar cell efficiency up to 6 percent by adding some impurities to the silicon solar cell. Later more advances in space programs and the 1970s energy crisis lead to more developments in the solar cell technologies. The solar cells' energy generation between 1988 and 2009, increased from 35 MW to 11.5 GW [3,13].

There are four major types of PV cells namely, mono-crystalline (or single crystalline), poly-crystalline, amorphous and organic cells. Nano PV is also a newly introduced kind of solar cells [12].

Solar cells are mostly produced out of copper, cadmium sulphide, gallium arsenide and cadmium telluride and etc. while thanks to its specific optical properties silicon holds the top position among these materials [12,14]. A typical silicon PV cell produces less than 3 W at a 0.5 V DC. Connecting PV cells in series results in PV modules ranged from a few to 300 W. Attaching the module strings in series and parallel one can make PV arrays with a range of 100 W to kW [11].

Space crafts, marine navigation aids, telecommunication, cathodic protection, water pumping, remote area power supply (RAPS) systems and many others are among the various applications of PV cells [12,15,16].

The operation of a shaded PV cell can be described by diode equation. An I–V curve can clearly describe the performance of PV cell under different environmental conditions such as temperature and illumination [17].

An I–V characteristic equation is presented below:

$$I = I_l - I_s(e^{(qv/kT)} - 1) \tag{1}$$

$q = 1.6 \times 10^{-19}$ C and $k = 1.38 \times 10^{-23}$ J/K. I_s depends significantly on the cell temperature [11].

Cell current at various irradiance levels can be calculated by the following equation:

$$I_l(G) = \left(\frac{G}{G_o}\right) I_l(G_o) \tag{2}$$

G_o is 1 kW/m^2 at AM 1.5, $I_l(G_o)$ cell current at G_o.

The power extracted from a PV cell is the product of current and voltage.

$$P_{\text{cell}} = (I_{\text{cell}}) \cdot (V_{\text{cell}}) \tag{3}$$

The open circuit voltage is logarithmically dependant on the cell illumination level. The short circuit current also is dependent on cell illumination level [18]. For the maximum power produced by the solar cell, the following equation can be used.

$$P_{\max} = (I_m) \cdot (V_m) = (\text{FF}) \cdot (I_{sc}) \cdot (V_{oc}) \tag{4}$$

FF shows the quality of solar cell [19].

NOCT is the cell temperature when operating at open circuit, ambient temperature of 20 °C at AM 1.5 and irradiance of $G = 0.8$ kW/m^2 and wind speed not greater than 1 m/s [20].

$$T_c = T_a + \left(\frac{\text{NOCT} - 20}{0.8}\right) G \tag{5}$$

1.4. PV cell efficiency

The current range of commercial solar cells' efficiency is between 12 and 19%. A variety of factors such as temperature, exposure to sunlight, properties of sunlight, dirt, dust and etc. are efficacious in cell performance [15,21,22].

By increasing the solar radiation, V_{oc} increases logarithmically whereas the I_{sc} elevates linearly, as an upshot the resulting power increases. As the cell temperature increases the efficiency drops by lowering the V_{oc} and a slight decrease of I_{sc}. In order to increase the cell efficiency, the cell surface must be kept at lower temperatures and the dirt and dust should be removed from its surface [18,23]. However, texturing, passivation of the surface and adding anti reflecting materials can improve the performance [24]. The effect of various parameters on the solar cell functioning is summarized in Table 1.

Table 1
Summary of various influential parameters on PV cell performance [18,21–23].

Parameter	Dependency	Influential factor
Cell current	Dependent on	Irradiance and wavelength
V_{oc}	Logarithmically dependent on	Illumination
I_{sc}	Dependent on	Illumination
Fill factor	Increases by	I_l/I_s increase
Fill factor	Increases by	Series resistance decrease
Fill factor	Increases by	Shunt resistance increase
V_{oc}	Decreases by	Temperature rise
I_{sc}	Nearly constant by	Temperature rise
Fill factor	Decreases by	Temperature rise

To maximize the output power and the efficiency of solar cells simply the V_{oc}, I_{sc} and FF should be boosted up. Likewise while trying to maximize the I_l/I_s ratio, I_s must be kept minimum. Similarly in order to optimize I_l, one should maximize the diffusion length and junction width and minimize the reflection of incident photons.

The conversion efficiency of the solar cells can be formulated as following:

$$\eta = \frac{I_{\text{sc-max}} \cdot V_{\text{oc-max}}}{A_c(\text{irradinace level})} \tag{6}$$

Besides all the stated parameters, there are some overlooked omnipresent parameters such as deposition of dust, bird droppings, water stains, humidity and wind velocity which can affect the solar cell performance and rationally should be taken in to account for design purposes.

In this study the effect of dust, humidity and air velocity in terms of efficiency will be elaborated.

2. Effect of dust on PV cell performance

Dust is defined as the minute solid particles less than 500 μm in diameter. Minute pollens such as bacteria and fungi, and microfibers separated from clothes, carpets and fabrics are also known as dust when settled on surfaces. Dust deposition is a function of various environmental and weather conditions. Pedestrian and vehicular activities, volcanic eruptions, pollution and wind can lift up dust and scatter it into the atmosphere [25].

Dust settlement mainly relies on the dust properties (chemical properties, size, shape, weight, etc.) as well as on the environmental conditions (site-specific factors, environmental features and weather conditions). The surface finish, tilt angle, humidity and wind speed also affect the dust settlement [25,26].

There have been different studies conducted to investigate the effect of dust on solar cells. A wide range of reduction in performance have been reported including average reduction of 1% with a peak of 4.7% in a two-month period in united states [27], 40% degradation in a 6-month period in Saudi Arabia [28], 32% reduction in a 8-month time again in Saudi Arabia [25], 17%–65% reduction depending on the tilt angle in 38 days in Kuwait [29]. In another study done in Egypt 33.5%–65.8% reductions in performance have been announced in duration of one to six months exposure respectively [30]. More specifically in the tropical climate of Thailand, 11% reduction in transmittance for a period of one month has been reported [31]. The direct beam solar radiation on tilted panels covered with dust is formulated for design purpose calculations [32].

This can be concluded from the results that modules tilted with larger angles let less dust get accumulated on surfaces, leading to less transmittance drop. It can also be concluded that finer particles affect the PV efficiency more considerably than coarser particles.

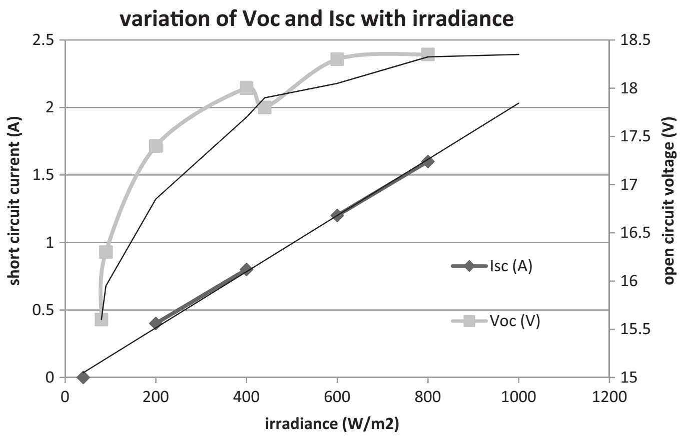

Fig. 2. Variation of V_{oc} and I_{sc} with irradiance level [34].

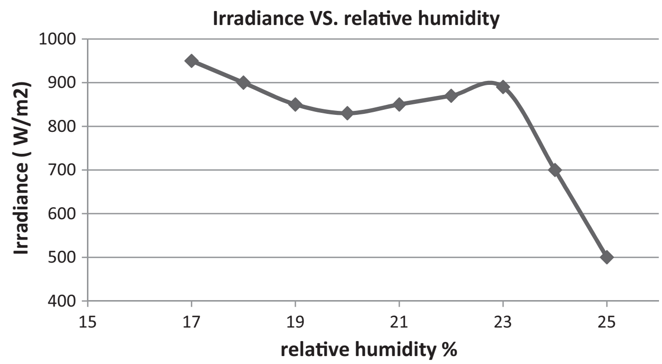

Fig. 3. Variation of irradiance level with relative humidity [34].

As the wind speed increases, more dust deposition will occur while the dust deposition relative to the ground decreases [33]. Excessive dust accumulation results in deterioration of solar cell's quality and fill factor. Dust promotes dust, so that the performance of PV modules declines exponentially with more dust pile up [26]. High humidity also helps formation of dew on the solar cell surface leading to more facile dust coagulation [25].

3. Effect of humidity on PV cell performance

In analyzing the effect of humidity, two scenarios need to be considered. The first scenario is the effect of water vapour particles on the irradiance level of sunlight and the second scenario is humidity ingression to the solar cell enclosure.

When the light hits water droplets, three cases may happen. It may be refracted, reflected or diffracted. These effects plunges the reception level of the direct component of solar radiation. Humidity alters the irradiance non-linearly and irradiance itself causes little variations in V_{oc} in a non-linear manner and large variations in I_{sc} linearly. Referring to Eq. (6) and knowing that humidity degrades I_{sc} but has insignificant effect on V_{oc} the power output, efficiency drops [34]. For a better understanding of the effect of humidity on irradiance and irradiance on voltage and current are demonstrated in Figs. 2 and 3 respectively which are related to a case study in Nigerian tropical climate.

Non-uniform distribution and wide range of water vapour particle sizes in the atmosphere are the grounds for the nonlinear deviations of irradiance with relative humidity. Greater scattered angles occur with smaller water vapour particles. More diffraction is also the result of more water vapour particles in the atmosphere. It is crystal clear that with much higher relative humidity of tropical countries like Malaysia we will have a disappointingly sharper drop in irradiance level. Wind speed has a reverse effect on relative humidity which in turn affects the received irradiance [34].

In the second approach to the humidity effect on solar cell performance, moisture ingression will be studied. When PV cells are exposed to humidity for long term there will be some degradation in performance, as it is seen in Fig. 4. It has been observed that the high content of water vapour in the air causes encapsulant delamination [35].

Generally, there are two module failure mechanisms based on the type of PV technology implemented. Failure at cell interconnections or cracked cells happens in crystalline silicon cells and failure at scribe lines is the dominant cause of cell thin film modules degradation. Consequently, embrittlement of the encapsulant material and corrosive moisture are the influential factors of the mentioned degradations for crystalline silicon cells and thin films respectively. Hot and humid weather can expedite these deterioration processes [36].

The performance degradation is a result of passivated PV cells surface leading to I_{sc} degradation, while having no considerable effect on V_{oc} [35].

In rare cases V_{oc} surges drastically which is surprisingly strange. One reasonable explanation to this phenomenon is that the water droplets trapped inside the cell act like magnifier lenses that focus the sunlight. By the same token, the water vapour particles function

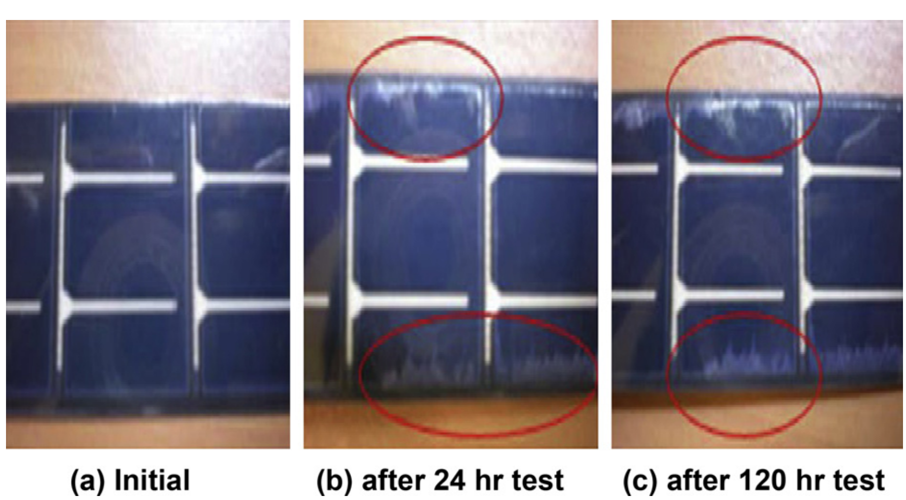

Fig. 4. Devastating moisture penetration into solar cells [35].

Table 2
A brief summary of different influential parameters on the PV cell performance.

	Dust	Humidity	Air velocity	Efficiency
Dust	More dust settlement	Insignificant effect	Insignificant effect	Drops
Humidity	Causes more dust coagulation	–	Insignificant effect	Mostly drops Surges occasionally
Air velocity	More dust depositionLess dust deposition	Decreases	–	Improves

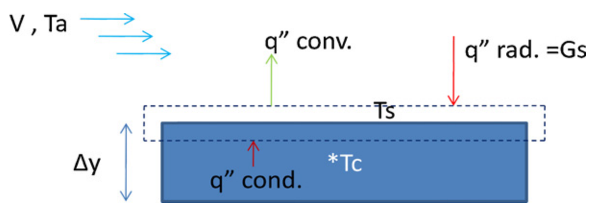

Fig. 5. The heat transfer scheme of a typical PV cell, control surface.

as barriers preventing received sunlight from escaping out of the cell enhancing EHP generation rate [35].

Some precautionary measures can be introduced to reduce the moisture ingression into cell chambers such as using edge sealants and choosing low ionic conductive material for encapsulant [37].

4. Effect of wind velocity on PV cell performance

As stated previously, the PV cell performance is sharply sensitive to cell temperature. PV cell temperature is a function of different parameters such as weather variables (ambient temperature, wind velocity, etc.), solar irradiance, cell material and system dependent properties (glazing cover transmittance, plate absorption, etc.). Cell temperature can be expressed by following function:

$$T_c = f(T_a, V, G_s, \text{material}, \ldots) \tag{7}$$

The conversion efficiency can be formulated by Eq. (8):

$$\eta = \eta_{T_{ref}}[1 - \beta_{T_{ref}}(T_c - T_{ref})] \tag{8}$$

$\eta_{T_{ref}}$ is the electrical efficiency of module at T_{ref} and 1000 W/m^2 solar radiation.

$\beta_{T_{ref}}$ depends on PV material and T_{ref}. The latter two parameters are usually specified by the cell manufacturer [19]. In order to calculate the cell temperature, Eq. (5) can be employed.

As indicated in Fig. 5, there are three modes of heat transfer occurring into or out of the control surface of a typical PV cell. To simplify, the heat transfer is assumed one dimensional and the velocity V, on top of the PV surface is considered merely horizontal and uniform.

Conservation of energy equation should be using Eq. (9):

$$q''_{cond.} = q''_{conv.} - G_s \tag{9}$$

For conduction and convection heat transfer we have:

$$q''_{cond.} = \frac{-2k(T_c - T_s)}{\Delta y} \tag{10}$$

$$q''_{conv.} = h(T_s - T_a) \tag{11}$$

Using an appropriate correlation [38] for external turbulent flow convection over flat plates, we can find the corresponding Nusselt number:

$$\text{Nu}_x = 0.0296\, Re_x^{4/5} Pr^{1/3}, \quad 0.6 < Pr < 60 \tag{12}$$

Knowing that Reynolds number is calculated as below:

$$Re_x = \frac{V \cdot x}{\nu} \tag{13}$$

The amount of Pr and ν should be read from tables of atmospheric air at film temperature which is the average of surface and ambient temperature.Nusselt number is related to convective heat transfer coefficient via the following equation:

$$h = \frac{\text{Nu} \cdot k}{L} \tag{14}$$

L is the length of solar cell in meters.

Finally the energy conservation principal can be implemented using Eq. (15):

$$\frac{-2k(T_c - T_s)}{\Delta y} = h(T_s - T_a) - G_s \tag{15}$$

As the air velocity increases the cell temperature will drop and better PV cell efficiency will be resulted.

The temperature dependency of PV cell performance is greatly related to cell type. As it is expected for the hot and humid temperature of Malaysia, mono and multi crystalline silicon cells have higher efficiencies compared to amorphous silicon and copper indium diselenide (CIS) solar cells with CIS efficiency higher than amorphous silicon efficiency. Performance ratio defined in Eq. (16) is just the reverse, meaning that CIS and amorphous cells have higher performance ratios compared to crystalline solar cells. It can be suggested that for Malaysian climate the latter two kinds of PV cells should be promoted and installed [39].

$$\text{Performance ratio} = \frac{P_{mea}/P_{max}}{G/1000} \tag{16}$$

5. Summary and conclusion

To recapitulate, it can be mentioned that dust deposition and settlement on the surface of PV cells can drop the efficiency. Likewise almost always humidity causes degradation in solar cell efficiency. By increased wind velocity more heat can be removed from the PV cell surface. In the same vein, higher air velocity lowers the relative humidity of the atmospheric air in the surroundings which in turn leads to better efficiency. On the contrary, wind lifts dust and scatters it in the environment resulting in shading and poor performance of PV cells. The summary of the results is brought in Table 2.

In short, dust, humidity and air velocity go hand in hand in affecting the performance of PV cells and each should not be studied separately in estimating the cell efficiency ignoring the effects of the other.

6. Future direction

This study reviewed a number of parameters important to operation of solar cells. In the future studies, the experiments can be conducted based on the simultaneous effect of these parameters. According to the outcome of these probable experiments a number of correlations including different factors can be adopted. Consequently, experimental results, correlations and simulations relying on mathematical modelling which cover different factors seem to be the possible results of future researches.

References

[1] Gueymard CA. The sun's total and spectral irradiance for solar energy applications and solar radiation models. Solar Energy 2004;76(4):423–53.
[2] Chen ZS, Mo SP, Hu P. Recent progress in thermodynamics of radiation—exergy of radiation: effective temperature of photon and entropy constant of photon. Science in China Series E: Technological Sciences 2008;51(8): 1096–109.
[3] Goetzberger A, Hebling C, Schock HW. Photovoltaic materials: history, status and outlook. Materials Science and Engineering R: Reports 2003;40(1): 1–46.
[4] Gottschalg R, Infield D, Kearney M. Experimental study of variations of the solar spectrum of relevance to thin film solar cells. Solar Energy Materials and Solar Cells 2003;79(4):527–37.
[5] <http://en.wikipedia.org/wiki/File:Solar_Spectrum.png>; 25 July 2011.
[6] Li H, Ma W, Wang X, Lian Y. Estimating monthly average daily diffuse solar radiation with multiple predictors: a case study. Renewable Energy 2011.
[7] Gueymard CA. Direct and indirect uncertainties in the prediction of tilted irradiance for solar engineering applications. Solar Energy 2009;83(3): 432–44.
[8] Zagury F, Goutail F. Spectral analysis of extinguished sunlight. New Astronomy 2003;8(6):537–48.
[9] Kudish AI, Evseev EG. The analysis of solar UVB radiation as a function of solar global radiation, ozone layer thickness and aerosol optical density. Renewable Energy 2010.
[10] Virtuani A, Lotter E, Powalla M. Influence of the light source on the low-irradiance performance of Cu (In: Ga) Se2 solar cells. Solar Energy Materials and Solar Cells 2006;90(14):2141–9.
[11] Messenger RA, Ventre J. Photovoltaic systems engineering. CRC; 2004.
[12] Razykov TM, Ferekides CS, Morel D, Stefanakos E, Ullal HS, Upadhayaya HM. Solar photovoltaic electricity: current status and future prospects. Solar Energy 2011;85(8):1580–608.
[13] Jager-Waldau A. Progress in chalcopyrite compound semiconductor research for photovoltaic applications and transfer of results into actual solar cell production. Solar Energy Materials and Solar Cells 2011;95(6):1509–17.
[14] Contreras MA, Romero MJ, Noufi R. Characterization of Cu (In, Ga) Se2 materials used in record performance solar cells. Thin Solid Films 2006;511:51–4.
[15] Mekhilef S, Saidur R, Safari A. A review on solar energy use in industries. Renewable and Sustainable Energy Reviews 2011;15(4):1777–90.
[16] Kalogirou SA, Tripanagnostopoulos Y. Industrial application of PV/T solar energy systems. Applied Thermal Engineering 2007;27(8–9):1259–70.
[17] Mahmoud MM. Transient analysis of a PV power generator charging a capacitor for measurement of the IV characteristics. Renewable Energy 2006;31(13):2198–206.
[18] Meral ME, Dinçer F. A review of the factors affecting operation and efficiency of photovoltaic based electricity generation systems. Renewable and Sustainable Energy Reviews 2011;15(5):2176–84.
[19] Skoplaki E, Palyvos JA. On the temperature dependence of photovoltaic module electrical performance: a review of efficiency/power correlations. Solar Energy 2009;83(5):614–24.
[20] Alonso García M, Balenzategui J. Estimation of photovoltaic module yearly temperature and performance based on Nominal Operation Cell Temperature calculations. Renewable Energy 2004;29(12):1997–2010.
[21] Sánchez Reinoso CR, Milone DH, Buitrago RH. Efficiency study of different photovoltaic plant connection schemes under dynamic shading. International Journal of Hydrogen Energy 2010;35(11):5838–43.
[22] Nagae S, Toda M, Minemoto T, Takakura H, Hamakawa Y. Evaluation of the impact of solar spectrum and temperature variations on output power of silicon-based photovoltaic modules. Solar Energy Materials and Solar Cells 2006;90(20):3568–75.
[23] Park K, Kang G, Kim H, Yu G, Kim J. Analysis of thermal and electrical performance of semi-transparent photovoltaic (PV) module. Energy 2010;35(6):2681–7.
[24] Iyengar VV, Nayak BK, Gupta MC. Silicon PV devices based on a single step for doping, anti-reflection and surface passivation. Solar Energy Materials and Solar Cells; 2010.
[25] Mani M, Pillai R. Impact of dust on solar photovoltaic (PV) performance: research status, challenges and recommendations. Renewable and Sustainable Energy Reviews 2010;14(9):3124–31.
[26] Kaldellis JK, Kapsali M. Simulating the dust effect on the energy performance of photovoltaic generators based on experimental measurements. Energy 2011;36(8):5154–61.
[27] Hottel H, Woertz B. Performance of flat-plate solar-heat collectors. Transactions of the American Society of Mechanical Engineers (USA) 1942:64.
[28] Nimmo B, Said SAM. Effects of dust on the performance of thermal and photovoltaic flat plate collectors in Saudi Arabia—preliminary results. In: Veziroglu TN, editor. Proceedings of the 2nd Miami International Conference on Alternative Energy Sources, Dec. 10–13. 1979. p. 223–5.
[29] Sayigh A, Al-Jandal S, Ahmed H. Dust effect on solar flat surfaces devices in Kuwait. In: Furlan C, Mancini NA, Sayigh AAM, Seraphin BO, editors. Proceedings of the Workshop on the Physics of Non-Conventional Energy Sources and Materials Science for Energy, 1985 Sept. 2–20. 1985. p. 353-367.
[30] Hassan A, Rahoma U, Elminir H, Fathy A. Effect of airborne dust concentration on the performance of PV modules. Journal of the Astronomical Society of Egypt 2005;13(1):24–38.
[31] Mastekbayeva G, Kumar S. Effect of dust on the transmittance of low density polyethylene glazing in a tropical climate. Solar Energy 2000;68(2):135–41.
[32] Al-Hasan AY. A new correlation for direct beam solar radiation received by photovoltaic panel with sand dust accumulated on its surface. Solar Energy 1998;63(5):323–33.
[33] Goossens D, Van Kerschaever E. Aeolian dust deposition on photovoltaic solar cells: the effects of wind velocity and airborne dust concentration on cell performance. Solar Energy 1999;66(4):277–89.
[34] Gwandu BAL, Creasey DJ. Humidity: a factor in the appropriate positioning of a photovoltaic power station. Renewable Energy 1995;6(3):313–6.
[35] Tan CM, Chen BKE, Toh KP. Humidity study of a-Si PV cell. Microelectronics Reliability 2010;50(9–11):1871–4.
[36] Kempe MD. Modeling of rates of moisture ingress into photovoltaic modules. Solar Energy Materials and Solar Cells 2006;90(16):2720–38.
[37] Sugimura RS, Wen LC, Mon GR, Ross RS. Test techniques for voltage/humidity-induced degradation of thin-film photovoltaic modules. Solar Cells 1990;28(2):103–14.
[38] Incropera FP, DeWitt DP. Fundamentals of heat and mass transfer. New York, NY: John Wiley & Sons Inc.; 2002.
[39] Amin N, Lung CW, Sopian K. A practical field study of various solar cells on their performance in Malaysia. Renewable Energy 2009;34(8):1939–46.